

Fluid Mechanics of Capillary-Elastic Instabilities in Microgravity Environment

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The aim of this project is to investigate the closure and reopening of lung airways due to surface tension forces, coupled with airway elasticity. Airways are liquid-lined, flexible tubes and closure of airways can occur by a Rayleigh instability of the liquid lining, or an instability of the elastic support for the airway as the surface tension of the air-liquid interface pulls the tube shut, or both. Regardless of the mechanism, the airway is closed because the liquid lining has created a plug that prevents axial gas exchange. In the microgravity environment, surface tension forces dominate lung mechanics and would lead to more prevalent, and more uniformly distributed airway closure, thereby creating a potential for respiratory problems for astronauts.

Once closed the primary option for reopening an airway is by deep inspiration. This maneuver will pull the flexible airways open and force the liquid plug to flow distally by the incoming air stream. Airway reopening depends to a large extent on this plug flow and how it may lead to plug rupture to regain the continuity of gas between the environment and the alveoli. In addition to mathematical modeling of plug flows in liquid-lined, flexible tubes, this work has involved benchtop studies of propagating liquid plugs down tube networks that mimic the human airway tree. We have extended the work to involve animal models of liquid plug propagation in rat lungs. The liquid is radio-opaque and x-ray video imaging is used to ascertain the movement and distribution of the liquid plugs so that comparisons to theory may be made. This research has other uses, such as the delivery of liquids or drugs into the lung that may be used for surfactant replacement therapy or for liquid ventilation. Surfactant replacement therapy is used in prematurely born infants who have a surfactant deficit and receive instillation of surfactants in a liquid form directly into their tracheas. Liquid ventilation is a new and potentially life-saving method of ventilating critically ill patients with perfluorocarbon liquids, instead of air.

Our investigations of preventing airway closure involve the use of an oscillatory shear flow in the core fluid (air) of a liquid-lined tube. Using mathematical modeling, we impose a sinusoidal shear stress on the air-liquid interface which can come from the air flow during normal breathing or assisted breathing by a ventilator or chest-wall vibrator, for example. The oscillations can stabilize the Rayleigh instability so that closure does not occur. In addition to potential applications in microgravity, maintaining airway patency in patients on ventilators is of great concern in medical practice. For example, the use of high frequency ventilation in infants has been successful, and the novel stabilization mechanism we are exploring may be an important, yet unrecognized reason for it.

These flow and stability problems are common to other applications. As a technologically related example, there are two air-liquid surfaces in annular extrusion methods for manufacturing small hollow fibers. Such flows may become unstable for a variety of reasons, and current research addresses how stabilization may be achieved from imposed external oscillations. Also, there are methods of manufacturing optical fibers in which there is an inner plug core of liquid and an outer annulus of a different liquid co-extruded simultaneously, one around the other. An important problem in co-extrusion is to have a smooth interface between the materials so that the desired mechanical and optical properties are achieved. Our work is also related to the more general problem of interfacial flows in poro-elastic media, an important engineering and technological field.